# BRUSH WEAR AT HIGH ALTITUDES

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Letter on front cover:

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# BRUSH WEAR AT HIGH ALTITUDES

by

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May 24, 1954

Professor Leicester F. Hamilton
Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge 39, Massachusetts

Dear Professor Hamilton:

In accordance with the regulations of the faculty, I hereby submit a thesis entitled Brush Wear at High Altitudes in partial fulfillment of the requirements for the degree of Naval Engineer.

Luigi Coluccciello

## ACKNOWLEDGMENTS

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BRUSH WEAR AT HIGH ALTITUDES by LUIGI COLUCCIELLO

Submitted to the Department of Naval Architecture and Marine Engineering on May 24, 1954 in partial fulfillment of the requirements for the degree of Naval Engineer.

## ABSTRACT

The wear of carbon brushes is influenced by many environmental factors. Two altitude variables, water vapor and oxygen pressures, are among such factors which can seriously affect the useful life of carbon brushes. It has been found that the application of certain metallic halides to carbon brushes will often permit them to operate at higher altitudes than otherwise possible.

The integrated influences of the many factors affecting brush wear are reflected in the behavior of the characteristic surface film which forms on the commutator (or slip ring). One theory of surface film behavior holds that the surface film builds up to equilibrium thickness by a random process of chemical reduction of the film under the brush surface and oxidation or film formation when the commutator emerges from under the brush. It would appear then that for a given altitude condition the amount of carbon brush area and its distribution around the commutator would determine the amounts of oxidation and reduction. This would determine the equilibrium film thickness and the rate of brush wear. If the amount of chemical reduction was sufficiently high for the given altitude condition the film would vanish and the brush would "dust" or wear away in a few hours. Under varying altitude conditions, the brush configurations producing the greater chemical reduction would cause dusting at the lower altitudes. In addition, if the chemical reactions taking place in the formation of surface films with halide impregnated brushes have time durations of approximately the same magnitude as the time necessary for a spot on the commutator to transit the distance between adjacent brushes, then the surface film stability and brush wear could be influenced by the commutator speed. This investigation sought to find if these relations existed.

The planned test procedure was to run successive brush wear tests at increasing simulated altitudes above 35,000 feet until brush dusting occurred for three brush configurations. These configurations consisted of a single brush, two symetrically positioned brushes,

and four symetrically positioned brushes. None of the test brushes were electrically loaded.

The second phase of the testing was to check the brush wear rates with four symetrically positioned brushes at varying altitudes and commutator speeds.

The halide treated test brushes showed negligible wear during all tests. In contrast, the motor test brushes, which were also impregnated with metallic halides for high altitude operation, dusted away in a few hours. Despite the obvious differences in the manner in which the two sets of brushes were operated, there is no readily available explanation for the difference in wear rate because of the very complex dynamic characteristics of the surface films. Considerably more testing is required before a positive conclusion can be made about the relationships of brush area, its distribution, and of commutator speed to brush wear.

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Title: Assistant Professor of Electrical Engineering

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# INTRODUCTION

The friction of carbon brushes sliding on copper surfaces is radically influenced by many environmental factors. For instance, sufficient reduction in the pressure of the surrounding oxygen or water vapor will increase the sliding friction such that the brush wear rate may increase by a factor of a thousand or so of the normal wear rate. Occasionally such conditions are encountered at sea level. They are nearly always encountered at altitudes above 30,000 feet. Around 1942 this brush wear problem imposed a severe limitation on operation of military aircraft. The range of the aircraft was drastically reduced with increasing altitude due to failure of components dependent on commutator and slip-ring type electrical machinery. Furthermore, the reliability of the aircraft decreased at increasing altitude since the inception and rate of rapid brush wear could not be predicted.

Prior to World War II some investigations had been made concerning the influence of adsorbed gases on sliding friction(1), the electrical characteristics of sliding contacts(2), and the prevention of brush disintegration under sea-level conditions(3). However, intensive study of the factors affecting brush wear did not commence until the early part of World War II. It was already known that good brush performance was dependent on such mechanical features as the shape of the brush faces,

the spring loading, and brush angle relative to the commutator. However, the new brush wear problem was no longer one of macrophysical considerations, but of molecular surface forces.

<u>The Surface Film</u>

("Normal conditions" herein refers to the average atmospheric condition encountered at sea level.)

If a carbon brush is applied to a new commutator or slip-ring the machine will not operate properly until the machine is operated under no load or under light electrical load for a few hours to "run-in" the brushes. This preliminary step is necessary to seat the brushes and to allow a surface film to form on the copper surface.

Van Brunt and Savage[(4), (5)] made a chemical analysis of a typical surface film. This film consisted primarily of cuprous oxide (65.8 per cent) and carbon (22.1 per cent). Van Brunt and Savage also computed the cuprous oxide film to be $2.1 \times 10^{-5}$ mm. thick and the carbon film to be $3.3 \times 10^{-5}$ mm. thick. They found the carbon in a separate strata from the current collector film, with the carbon making up the upper layer, and the collector film the lower. A typical film is generally a glossy reddish-purple color. Vernon[(6)] has reported that a cuprous oxide film of 210 A° would be between orange and bluish purple in color. The carbon film then is essentially transparent, while the cuprous oxide film is opague, its color giving an approximate indication of its thickness.

The surface film is of extreme functional importance, but at present the manner of its formation is unknown. Electric current is not a

necessity in its formation. Nor does carbon need a cuprous-oxide film as a base in adhering to a metallic collector. A thin carbon film can be laid down on a clean copper bar with a single stroke of a carbon rod. If there is any oxide in this film, it is not at all evident.

Conditions influencing the stability of the cuprous oxide layer will influence the voltage contact drop and/or the rate of brush wear. Certain gases and vapors will cause the cuprous oxide layer to thicken, raising the voltage drop at the surface film. Alternately - and the problem of interest here - if the environment causes the surface film to wear away faster than it can build up, the brush wear will increase tremendously.

The surface film then has two apparent primary functions:

(a) provide a smooth sliding, low friction surface;

(b) allow current collection from the metal collector, through itself, and to the brush surface.

Carbon (graphite) by itself is not a good lubricant. Carbon can be shown to seize when drawn across a metal, carbon, or cardboard surface under the proper environment. In such a non-lubricating state, therefore, the intersurface molecular forces are very high unless the surfaces can be separated by a film with which the carbon does not seize. Fortunately carbon is normally in a lubricating condition. We depend on this when we write with a pencil or when we go about "running-in" a set of brushes on a new electric machine. It is generally agreed that for satisfactory performance, a good uniform surface film must

exist on the commutator or slip-ring. However, many investigators have shown that carbon sliding on clean copper without surface films will not dust (wear away at a visible rate) under normal atmospheric conditions. True, a surface film will build up and reduce friction or intersurface forces; but note that the lubricant state of the carbon itself is sufficient to prevent seizure initially before the surface film has formed. Therefore, it is speculated that under normal conditions the film is necessary for sparkless current collection and to reduce friction from moderate to small values, but not to prevent the enormous friction or seizure which results in brush dusting. If the surface film will form, then the carbon is in a lubricating state and does not need the film to prevent surface seizure. Therefore, when a normal surface film becomes unstable, this is as much an indication of the non-lubricating condition of the carbon as it is of the changed environment. The film then is no longer able to prevent the moving brush from destroying the film itself. No one has suggested that the film will disappear in rapid brush wear environment without the brush sliding upon it. Therefore, although it is of great importance to keep the surface film uniform and of proper thickness, it should be remembered that any success in doing so is basically a restoration of the lubricating condition of the brush. All major efforts so far have been aimed directly at maintaining this surface film to separate the copper and carbon surface, prevent seizure by surface molecules, and thus prevent brush dusting. However, this writer is of the opinion that a disappearing

surface film is merely evidence of the non-lubricating state of the carbon brush and that if the film were removed when the brush were in a lubricating condition, the surfaces would not seize. Admittedly, however, there are times when the carbon brush is in a non-lubricating state that the surface film will reduce the rate of brush wear (during the time of its own destruction) so that a time lag is introduced before dusting begins. This time lag may be sufficient for an aircraft to operate above its "brush ceiling" and then return to a lower safe altitude where the surface film will again build up to its normal thickness.

<u>Effect of Adsorption Films on Carbon Lubrication</u>

Some investigators[4] attempted to explain the normal lubricating state of carbon by theorizing that the carbon adsorbed a monolayer of the necessary gas, which gas then satisfied the surface valence of the carbon. Many tests have since been made to determine which particular gases could give this lubricating effect, and what pressures were required. A necessary precaution in such testing is the attainment of clean metal surfaces and brushes purged of previous gases. The metal disk can be cleaned by heating to drive off adsorbed gases and then applying large currents to the brushes to "electrically clean" the surface.[4] The latter step apparently destroys the thin oxide film which forms even when copper is exposed to the atmosphere at room temperature. Vernon[6] has shown that a film thickness of $1.05 \times 10^{-7}$ cm. forms on copper heated in air for one hour at 130° F. This film is transparent and therefore not easily detected. Savage[7] found it sufficient to clean

the copper surfaces with a solution of sodium carbonate and then rinsing. This apparently avoids the formation of a thick tarnish film produced by the baking process and perhaps destroys the thin film formed since the machining process. If the copper disk is installed in the test apparatus carefully and without undue delay, it can be considered sufficiently clean. In all cases the brushes should be freed of contaminants either by baking or by de-gassing in a vacuum.

Van Brunt and Savage(4) found that with no current in carbon brushes sliding on a copper disk, high friction and excessive brush wear prevailed in a vacuum or atmospheres of dry hydrogen, dry nitrogen, or low pressure dry oxygen. In every case this rapid brush wear could be stopped by raising the surrounding water vapor or oxygen pressure to a certain minimum value. Therefore, two principal variables controlling the lubricating ability of carbon are water vapor and oxygen pressures, two of the altitude variables. The lubricating effects of water vapor and oxygen are additive. It was found that the dry oxygen pressures required to stop brush dusting ranged from 300 to 500 mm. Hg. Others(8) have reported the minimum oxygen pressure required is as low as 190 mm. Hg. Nevertheless, this minimum pressure is greater than the partial pressure of oxygen at sea level, and consequently, rapid brush wear is encountered occasionally in regions exposed to extremely dry winter air.

Effects of Water Vapor Alone

Many experiments have been conducted to determine the coefficient of friction or brush wear rate versus water vapor pressure for carbon

brushes sliding on copper in a vacuum. The wear rate and coefficient of friction generally rise exponentially as the water vapor pressure is decreased below 3 mm Hg. This required minimum value of water vapor pressure led Van Brunt and Savage to suggest that "a kinetic equilibrium has been reached in which water molecules are condensing on a filled surface at the same average rate at which they are evaporating, thus effectively blocking off the interplanar forces of the graphite crystals." The lubricating ability of water vapor would then be a function of the number of water molecules available per unit volume and the duration that an average water molecule remained adsorbed to the carbon. Experimental results indicated that the life of a water molecule upon carbon to be less than $10^{-3}$ seconds. A computation based on the assumption that a minimum of 3 mm Hg. of water vapor pressure is required to form a monolayer of water molecules on the carbon surface, gave the average life of a water molecule upon carbon to be $0.7 \times 10^{-6}$ seconds. At this pressure about $1.4 \times 10^{21}$ molecules of water strike each square cm. of brush track each second and keep the carbon lubricated. Since others have found that brush friction and wear are a function of both water vapor pressure and brush temperature, the adsorption life of a water molecule on carbon is evidently also a function of temperature. For instance, while a brush around 60° C can be successfully lubricated with 3 mm Hg. of water vapor pressure, it requires 19 mm Hg. pressure at 135° C.

Pressure, Moisture, and Temperature Variations with Altitude

Figure 1 gives the variation of air pressure and air temperature with altitude as given by the National Advisory Committee for Aeronautics(13). Since the gaseous composition of the atmosphere changes extremely little with altitude, the oxygen pressure curve will be of the same shape with simply a scale factor change in pressure according to the partial pressure law for gases.

Figure 2 gives the range of variation in moisture content with altitude as given by the National Advisory Committee for Aeronautics(14). If moisture were the only consideration, aircraft could expect to encounter rapid brush wear above 12,000 feet, where the water vapor pressure is below 3 mm Hg. in summer time. However, the low temperature probably increases the lubricating effectiveness of the water vapor present, while the oxygen also tends to lubricate the brushes directly. Most of the rapid brush wear encountered early in World War II occurred above 20,000 feet.

Attempts to reduce brush wear under high-altitude conditions

Strenuous efforts were made during World War II to find a cure for rapid brush wear at high altitudes. Numerous tests failed to reveal any grade of untreated brush which would withstand high-altitude operation.

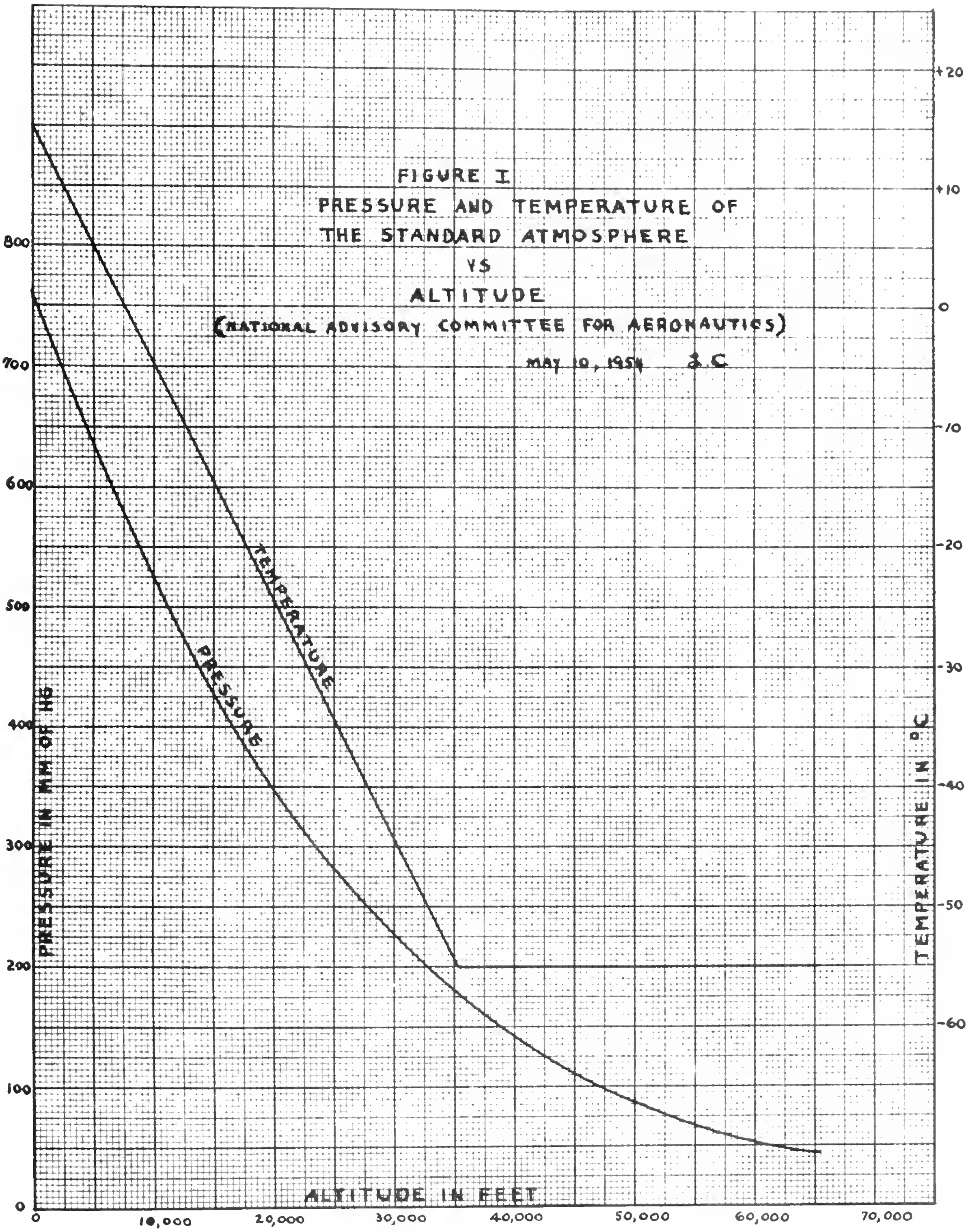
FIGURE I
PRESSURE AND TEMPERATURE OF
THE STANDARD ATMOSPHERE
VS
ALTITUDE
(NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS)
MAY 10, 1954
TEMPERATURE
PRESSURE
PRESSURE IN MM OF HG
TEMPERATURE IN °C
ALTITUDE IN FEET
0
100
200
300
400
500
600
700
800
+20
+10
0
-10
-20
-30
-40
-50
-60
0
10,000
20,000
30,000
40,000
50,000
60,000
70,000

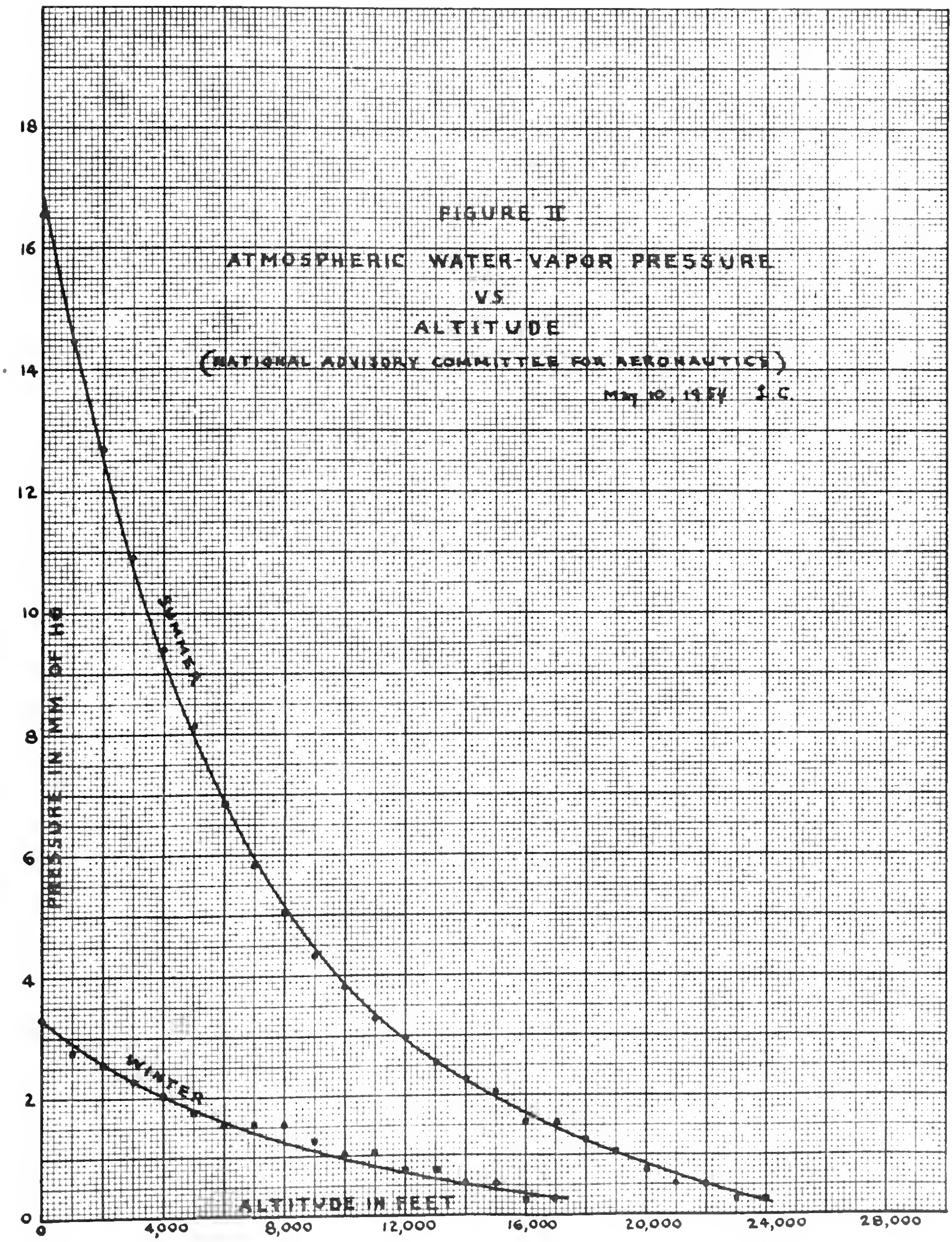
FIGURE II
ATMOSPHERIC WATER-VAPOR PRESSURE
VS
ALTITUDE
(NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS)
May 10, 1954 L.C.
PRESSURE IN MM OF HG
ALTITUDE IN FEET
SUMMER
WINTER
0
2
4
6
8
10
12
14
16
18
0
4,000
8,000
12,000
16,000
20,000
24,000
28,000

Continuing attempts have been made to find a substitute for copper for the metallic collector.[5],[9] The metal should be such, that in combination with carbon brushes, a surface film is developed of such composition that it remains stable under adverse conditions of low atmospheric pressure and low water vapor concentrations. There seems to have been no successful application of any material other than copper for commutators and slip rings thus far.

Some of the early attempts included the impregnation of existing brushes with organic lubricants such as paraffin. However, aircraft motors and generators are heavily loaded so that the high brush temperatures quickly drive the volatile waxes out of the brush.

The brushes were next impregnated with inorganic lubricants. Molybdenum sulfide failed due to lack of thermal and chemical stability.[10] Elsey[10] reports, however, that a test using lead iodide impregnation proved very successful. Such brushes developed a characteristic surface film which was stable under low oxygen and low water vapor conditions. It was presumed in this case that this was due to the formation of an intermediate compound, cuprous iodide. This compound is extremely unstable and probably readily oxidizes to cuprous oxide even in dry rarified atmospheres. It was shown that even a trace of iodine vapor released near an untreated brush operating under an atmosphere which normally caused dusting, would develop an oxide film and show low brush wear. Many other iodine compounds proved equally successful as impregnants. Tests with other metallic halides (iodides, bromides, chlorides, and fluorides) also proved effective.

Savage,[7] however, found that a cadium iodide impregnated brush would give a great increase in life under high altitude conditions only if it was given a preliminary run under an atmosphere which would not ordinarily cause dusting. Savage suggested that this was necessary to allow the surface film to form and for the adjuvant, or lubricant additive, to gradually enter the film where it could combine with the carbon to form a nearly permanent lubricant system. If, however, the treated brush was started on a clean copper surface under high altitude conditions, it would immediately dust away. Since most aircraft machinery was either tested on the ground, or received the necessary run-in while the aircraft was climbing through the low altitudes, this problem was never encountered on aircraft using brushes treated with halide salts. However, Savage also found that carbon brushes impregnated with $CdI_2$ were extremely sensitive to water vapor pressures less than 0.3 mm Hg. even though a good surface film had already been developed. Below this water vapor pressure brush wear rates increased by a factor of 100. The same was true for non-adjuvant brushes of course, but with such untreated brushes the critical water vapor pressure was 3 mm Hg. The only difference between the treated and untreated brush then appears to be in the minimum amount of water vapor required to put the brush in a lubricant state. The adjuvant added to the brush then is not a complete substitute for water vapor as the necessary brush lubricant. It is noteworthy that the minimum water vapor pressure required to prevent dusting of treated brushes as determined by Savage

does not ordinarily exist above about 19,000 feet. Oxygen pressure at such altitudes will aid in the lubrication of such brushes and raise this "brush ceiling." However, the allowable increase in altitude would appear to be only of small magnitude since oxygen has been found to be about one hundredth as effective as water vapor in lubricating treated brushes. For example, Savage was able to stop brush dusting of treated brushes with water vapor pressures of only 0.1 to 0.2 mm. Hg. but found 29 mm. Hg of Oxygen (the partial pressure of oxygen at 40,000 feet) insufficient.

Brushes impregnated with metallic halides gave generally successful performance on aircraft operating well above the "brush ceilings" indicated by Savage's work. Savage concluded that such brush installations operated above 25,000 feet only under conditions of unstable equilibrium, with the probability of their failure increasing with altitude. The continuing unpredictable behavior of new brush installations in aircraft at high altitudes or in high altitude test chambers gives some support to this belief and emphasizes the present inability to correlate properly all the factors contributing to rapid brush wear.

Some Difficulties Encountered with Halide Treatments

Because of the low heat conductivity of carbon brushes, extreme temperature gradients exist in brushes sliding on a metal surface. The temperature gradient varies with electrical loading, altitude conditions, and other factors, but even under "normal" conditions it remains high. In tests with carbon brushes sliding on alloy rings, the temperature at

the point of contact was sufficient to distill the lead and zinc out of the underlying leaded brass ring.[5] Such extreme temperatures have also prevented the use of some halides which are not sufficiently stable to withstand the temperatures found within the brushes. In some such cases the products of thermal decomposition react or deliquesce in air and leave a harmful residue.

Many other halides are not usable as impregnates because they adsorb water and dissolve in it.[10] Certain others are unsafe because, although not deliquescent, they are water soluble and may be accidentally leeched out if the brushes become wet. The use of some metallic halides has been ruled out because they produced non-uniform films, gave high contact drops, or were too difficult to incorporate into the brush material.

Proposed Theories on the Behavior of Surface Films

A number of theories have been presented to attempt to explain the behavior of surface films. Savage[7] supposed that the surface forces of carbon constitute the primary factors in brush lubrication. He also supposed that these surface forces of carbon atoms are different for the atoms within the face of a cleavage crystal compared to those for the atoms on the edge of the crystal. Consequently, the adsorption characteristics of the atoms within the main cleavage plane would differ from the adsorption characteristics of atoms at the edges of the planes. Then, as long as the carbon is in a lubricant atmosphere, both the edge and face atoms of the crystals are covered with adsorbed molecules of the lubricant.

Under such conditions the carbon crystals may be quickly stroked into an oriented layer or glazed film. It is known that the specular reflection of surface films is caused by the deposit of the brush and not due to polishing or buffing of the ring metal. If an untreated brush is operated in a "dry atmosphere", the carbon crystals have both their edge and face atoms uncovered and rapid brush wear will commence. If now a treated brush is run-in at low altitudes, the impregnant may gradually enter the film where it forms with the carbon into a nearly permanent lubricating system. The edges of the carbon crystals are presumed to be very hard and capable of destroying the surface film if uncovered. But the atoms in the crystal edges presumably also have larger surface forces so that the adsorption life of water molecules on an edge atom is greater than on a face atom. This then would explain why a treated brush that first had been allowed to develop a surface film at low altitude could be operated at altitudes well above (and at less water vapor pressures) those possible with untreated brushes. These assumptions can also be used to give a plausible explanation of the behavior of a treated brush under simulated high altitude conditions without a preliminary surface film build-up under normal conditions. However, this theory gives no insight on the cuprous oxide formation and behavior.

Elsey[10] has proposed a different mechanism by which the surface film is formed and maintained. During the machining of the copper commutator or slip-ring, a copper oxide film is formed on its surface. This initial film increases in thickness during the seating of the brushes. The

rate of growth of the surface film depends on many electrical, mechanical, and chemical factors. A very important factor is the temperature and type of contact at the brush-commutator interface. The temperature is largely a function of the heat generated by friction and by the electric energy dissipated across the boundary. Largely because of the freedom of the brush in its holder, the brush face will have a slightly larger radius of curvature than the commutator or slip ring. This difference in curvature and the impossibility of perfectly smooth surfaces confines the actual area of solid contact at a given instant to a relatively short span of the brush face. Conduction may also occur across adjacent areas of momentary accumulations of carbon or copper dust, or conduction may occur across minute air gaps in the form of an arc. But under any brush the electron transfer takes place at only a few highly localized areas, and vibration and mechanical irregularities cause these points of electron transfer to shift constantly about the brush face. These overheated areas of electrical contact react chemically with the copper oxide film to form metallic copper and carbon monoxide. The brush, as a chemically reducing agent, then becomes a de-filming rather than a filming agent. However, Elsey explains that when a minute area of freshly reduced metallic copper emerges from under the brush and contacts the air, it is immediately reoxidized. This same area may be reduced again when it passes under the next brush. However, since the actual electron transfer areas are small, a freshly oxidized spot may pass under several brushes without being reduced again, and thus, in

this manner the surface film can build up to equilibrium thickness. Since carbon is an excellent burnishing tool, a properly chosen brush polishes the oxide film as it is formed and prevents the roughening which would otherwise follow as a result of repeated oxidation and reduction. Elsey further proposes that perhaps the true function of water vapor is not that of a lubricant but of a catalytic agent promoting the oxidation of copper by the oxygen of the surrounding air.

Elsey's theory emphasizes the known dynamic character of the surface film. However, it contains no indication of how the thickening of the film is stopped to achieve equilibrium. Since growth is attributed to the probability that a freshly oxidized copper spot will miss being reduced during its next few brush transits, the film should continue to thicken until the probability of this occurrence has reduced. However, once the brush is fully seated this probability does not logically appear to be a function of film thickness. Admittedly, the film thickness equilibrium is a fact to be acknowledged, but it is not explained by the theory above. Nor does this theory explain how the surface film becomes separated into two layers, with the cuprous oxide layer covered by a carbon layer.

It would follow from the theory presented by Dr. Elsey that under certain altitude conditions and brush configuration, the rates of copper oxidation and reduction would be so finely balanced that any increase in the carbon area would increase the rate of reduction and thus destroy the cuprous oxide film. Of course, any decrease in oxygen and/or water vapor pressure would decrease the rate of oxidation and also destroy the surface

film. However, the purpose of this present investigation was to attempt to check the theory above by using the brush area and commutator speed as the variables.

Requirements for a High-Altitude Test Chamber

High-altitude simulating equipment may vary from small chambers designed to enclose only a slip-ring and brushes to very large elaborate chambers designed to test complete electrical machines while duplicating the loading, atmosphere, and ventilation which occur in service. However, the basic requirements of any chamber are that it must be able to:

1. control humidity
2. prevent contamination
3. control pressure and airflow
4. control temperature
5. provide electrical connections

Humidity control, of course, is of paramount importance because of the critical effect of small amounts of water vapor. For this reason, it is vital to prevent even very small leaks into the chamber. Brush wear is also very sensitive to numerous vapors which may either accelerate or retard this phenomena. These vapors may come from bearing greases, paints, insulating varnishes or other volatile matters not easily eliminated. Fresh dry air should be admitted to avoid the accumulation of such contaminating vapors. Considerable equipment may be required for the cleaning and drying process. It has been found by experience that

contamination will be negligible if the chamber air is changed 5-10 times per hour[11]. If clean dry air cannot be supplied to the chamber and recirculation must be used, then precautions should be taken to minimize contaminating vapors. In such cases thermal insulation, braid-covered leads, varnish-cloth tape and absorbent materials should not be placed inside the chamber.

Since the atmosphere changes very little in its percentage composition, even at altitudes of 60,000 feet, a simple reduction of pressure to equal that at various altitudes will also give the correct partial pressure of the atmospheric components for such altitudes. Because heat transfer conditions in the chamber are poor, very large temperature gradients are likely to exist. The average air ambient temperature determined at various points within the chamber should correspond to the temperature of the altitude being simulated.

## II PROCEDURE

### Plan of Attack

The first phase of this investigation was to determine if the rate of chemical reduction could be shown to be a factor in surface film stability by varying the carbon contact area. Three brush configurations were used - a single brush, two symetrical brushes, and four symetrical brushes. All brushes were of the same size and held in cartridge type holders radially positioned around a dummy commutator. All test brushes were of the same grade and impregnated with a metal halide.

The intended approach was to find the wear rate of a single brush at various simulated altitudes and if possible determine at what altitude dusting commenced. Next it was intended to follow the same procedure with two brushes and then again with four brushes. If the rate of oxidation and reduction were determining factors in surface film equilibrium, it would likely be borne out if dusting commenced at lower altitudes with an increasing number of brushes. It might also be reflected in a larger brush wear rate even before dusting commenced. In these preliminary tests none of the brushes were to be loaded electrically.

The second phase of the test program was planned to seek a possible relation between the surface film stability and commutator speed on the assumption that with increasing speed, either the ability to reduce the cuprous oxide or the ability to oxidize the reduced copper would be

impeded because of the time requirements of such reactions. Of course, this would depend on what chemical reactions take place with a metal halide impregnated brush, both under the brush face and on the exposed commutator surface at the existing temperatures. It is further assumed that the exposed commutator surface temperature is such that copper oxide tends to form rather than decompose, and that the temperature at the points of contact under the brush is such that copper oxide tends to be reduced by the carbon. The inability of measuring the temperatures at the points of electron transfer make these assumptions necessary but also rather arbitrary. It was then planned to choose several altitude conditions, and with a four brush configuration run brush wear tests at speeds ranging from 15,000 to 30,000 RPM with a dummy commutator one inch in diameter. The wear might very well increase slightly with increasing speed, but if the time required for oxidation exceeds the time of transit between brushes by any appreciable amount, then the surface film would be destroyed, and dusting would commence.

Adaptation of Vacuum Chamber

The basic piece of equipment used was the vacuum chamber (24" x 16" x 24") of the Meterology Department. With this chamber various altitudes can be obtained by turning the vacuum pump on and off as required. Temperature controls are automatic within the limits of the equipment. There are no provisions for humidity control nor for purification of inlet air. An electric fan inside the chamber is used to circulate the air to reduce temperature gradients and a large glass panel in the

door permits observation of the equipment inside the chamber. The chamber also contains two 110 volt 60 cycle outlets and four binding posts connected to binding posts located outside the chamber. .

The lack of equipment to supply clean dry air to the chamber was a serious handicap. It prevented both the variation of humidity to meet specified altitude conditions and it prevented flushing the chamber to avoid the build-up of contaminating vapors. However, since the basic variables to be tested were brush area and configuration, and commutator speed, it was thought that some correlation might still be observed if the water vapor pressure could be kept constant at some minimum value. Accordingly, ten hours before each test the apparatus was set up inside the chamber. Then two pounds of aluminum oxide was spread out to cover the entire base of the chamber and the door was bolted. Appendix (A) contains a sample calculation showing the moles of water vapor adsorbed by the aluminum oxide, assuming a single monolayer adsorption, compared to the moles of water vapor contained in the chamber at 72% relative humidity. It is evident that after standing for a period of ten hours, the chamber would be extremely dry. From the data on adsorbed films of water on the surface of graphite presented by Harkins, Jura, and Loeser[12] it appears that not even a small fraction of a monolayer of water molecules would have been available for adsorption by the brushes if they had been of relatively pure graphite.

The humidity inside the chamber could not be measured by sampling the exhausted air for two reasons. First, the vacuum pumps injected oil vapors into the exhausted air and would make such measurements extremely difficult. Secondly, there were some air leaks in the apparatus which could have caused very erroneous readings. The leaks could not be located but there was reason to suspect that most of the air was bleeding into the suction line between the chamber and the vacuum pumps, and very little, if any, was entering the chamber itself.

The degree of contamination by vapors could not be determined. However, the drive motor was not new and therefore the insulating varnishes should have been well dried out. No absorbent materials were permitted inside the chamber. The chamber was cleaned out between tests. However, cleaning was not completely possible between the close fitting fins of the cooling coils. Such inaccessible places were cleaned out with an air hose.

## Procedure for Each Test

The drive motor used in each test was a one-half horsepower series motor rated at 10,000 RPM full load. A belt drive between the motor and quill-shaft on which the dummy commutator was mounted permitted quill-shaft speeds up to 40,000 RPM. A variac in the motor circuit permitted speed control from outside the chamber. The RPM of the commutator was checked periodically through the chamber glass door by use of a strobotac. To avoid overheating of the motor under high-altitude conditions, the air intake on the self-ventilated motor was effectively

enlarged by removing the felt cloth air filter. A thermocouple was also attached to the motor shell to check its temperature during test.

For each test the desired number of brushes were inserted in the brush holders. Both the brushes to be tested and the drive motor brushes were then fully seated. All brushes were next measured with a micrometer jig and these measurements were recorded. The spring pressure on the test brushes was also measured. The test brushes were marked for indentification.

The test apparatus was then placed inside the chamber and the electrical and thermocouple connections were made. A thermometer was placed close to the brush test rig. Two pounds of dry aluminum oxide was then spread evenly over the bottom of the chamber and the chamber door was bolted. Each brush wear test was commenced after at least ten hours delay to allow the chamber to dry out. Figure III shows the equipment installed in the vacuum chamber.

Brush Identification

The drive motor brushes were identified as M-1 for the brush located near the air-intake and M-2 for the other brush. The test brushes were identified as T-1, T-2, T-3, and T-4 starting with the topmost brush and going clockwise while facing the end of the commutator. Both the motor brushes and the test brushes were treated for high-altitude operation. However, the motor brushes were of a different grade from the test brushes.

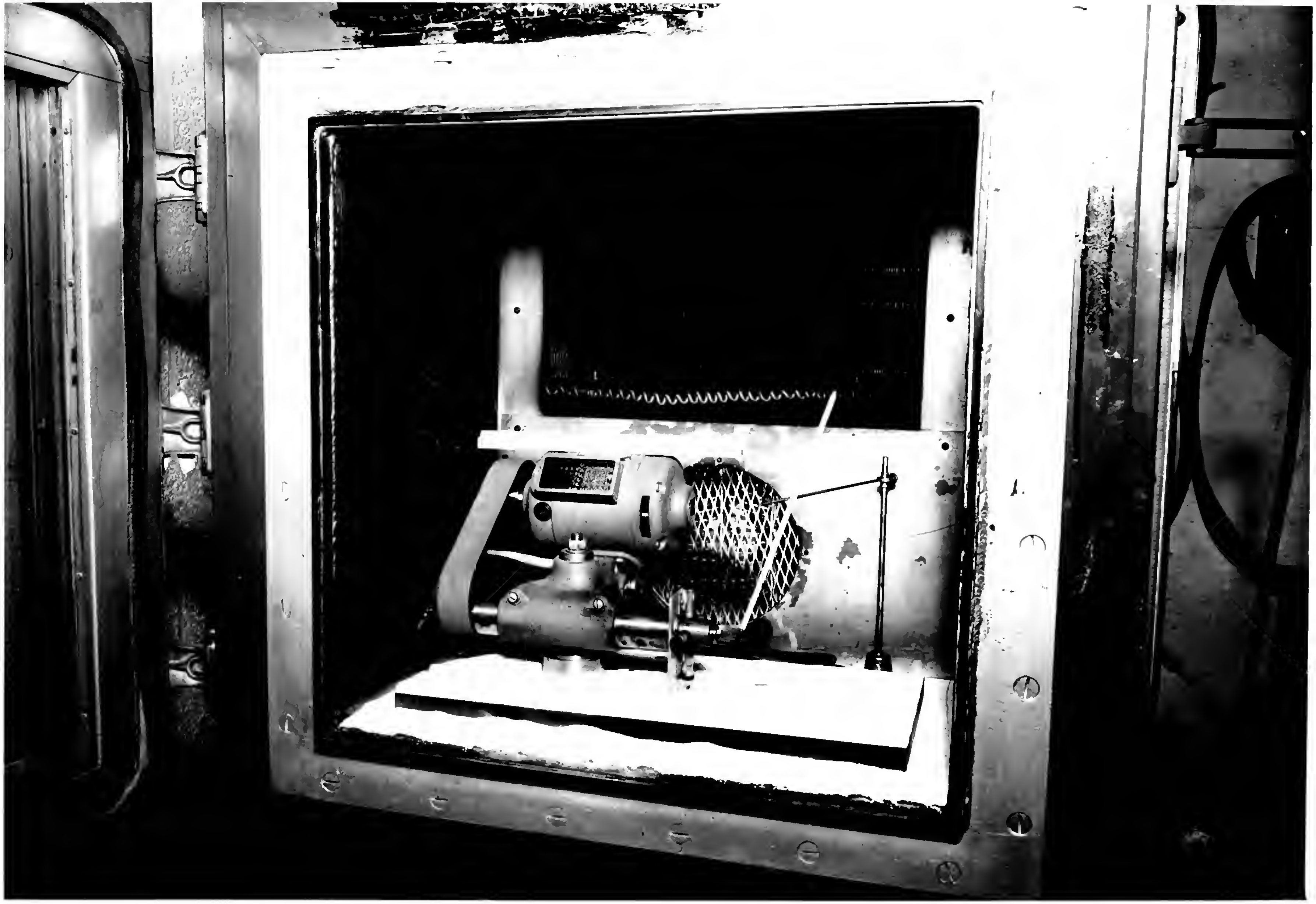

Figure 11 TEST APPARATUS INSTALLED IN ALTITUDE CHAMBER

## III RESULTS

### Test #1

Altitude corresponding to average pressure: 36,000 feet

Average temperature: -32° C

Commutator RPM: 14,000 RPM

Brush tested: T-2

Duration of test: 12 hours

| | T-2 | M-1 | M-2 |
|---|---|---|---|
| Total wear of brushes in inches | 0.0055 | 0.0985 | 0.0797 |

### Test #2

Altitude corresponding to average pressure: 60,000 feet

Average temperature: -12° C

Commutator RPM : 15,000 (changed from 14,000 due to severe vibration at that speed)

Brush tested : configuration of T-2 and T-4

Duration of test: 7.5 hours (test stopped due to dusting of motor brushes)

| | T-2 | T-4 | M-1 | M-2 |
|---|---|---|---|---|
| Total wear of brushes in inches | 0.0004 | 0.0018 | 0.3950 | 0.3390 |

Test #3

Altitude corresponding to average pressure: 60,000 feet

Average temperature : -10° C

Commutator RPM : 15,000

Brush tested : Configuration of T-1, T-2, T-3, and T-4

Duration of test : 3 hours (test stopped due to dusting of motor brushes)

| | T-1 | T-2 | T-3 | T-4 | M-1 | M-2 |
|---|---|---|---|---|---|---|
| Total wear of brushes in inches | .0008 | .0014 | .0008 | .0006 | .4117 | .4374 |

## IV DISCUSSION OF RESULTS

The continued failure of the motor brushes interrupted the tests at an early stage of this investigation and made it evident that testing could not be resumed until a successful brush type was found - assuming one existed. The obvious question is why did the motor brushes dust in the same atmosphere for which the test brushes showed neglibible wear? First some material differences must be pointed out. The test brushes were of a different grade and were not electrically loaded. The test brushes never developed a characteristic reddish-purple film on the commutator despite a long running-in period. Instead, this film appeared to be an extremely thin carbon cover over the copper. The surface film on the motor commutator appeared normal in every respect. These differences of course do not "explain" why the carbon molecules of the motor brushes behaved differently from those of the test brushes. The higher motor brush temperatures may have contributed greatly to the establishment of conditions which induced dusting. This is somewhat substantiated by the fact that the motor brushes did not dust in Test #1. True, this test simulated lower altitude conditions (36,000 feet) than tests #2 and #3 (60,000 feet). However, the moisture conditions for all three tests was undoubtedly the same, so that the effect of this very low water vapor pressure would far offset any change in oxygen pressure at

such altitudes. In test #1 however, the motor was running at a slightly slower speed and had to overcome the friction load imposed by only one test brush. Therefore, the motor brush temperatures in this test were very likely lower than for tests #2 and #3. It may also be worth-while to consider the differences in the behavior of the motor brushes and test brushes as a consequence of forces exerted upon the carbon by the electrons during the electron transfer between the carbon and copper. Just what the nature of this phenomena might be is unknown, but it is known that brush wear on d-c machines will differ between the positive and the negative brushes.

Since the motor brushes dusted away even though they were impregnated with a metallic halide for high altitude operation, two earlier conclusions were reinforced. First, the aluminum oxide was effective in maintaining the water vapor pressure inside the chamber below a very low value - in this case probably below 0.2 mm. Hg. Secondly, the leaks into the chamber were probably too small to affect the tests. The larger leaks which were known to exist probably were located between the chamber and vacuum pumps.

No special precautions were taken to clean the dummy commutator. However, the objective of these tests did not seem to require this, provided that all such variables which could not be adequately evaluated were kept as nearly the same as possible throughout the tests. In the particular testing procedure used here, the commutator would have been able to acquire a tarnish while standing inside the chamber during the drying

out period. The same problem was encountered with the brushes and may have had a considerable influence on the results. A baking of the brushes would have purged them of much excess air and moisture. However, they would have regained most of the air and moisture during the chamber drying out period. In the actual testing that occurred, the hotter electrically loaded brushes probably drove off most of their adsorbed air and moisture. This may not have occurred on the test brushes despite the presence of the aluminum oxide.

The heat generated by the test equipment prevented the chamber temperature from meeting the altitude requirement in all three tests. However, this is not considered a very important factor in the results since the humidity effect was much more predominant.

## V CONCLUSIONS AND RECOMMENDATIONS

Due to the failure of the motor brushes, no conclusions can be made about the original question which prompted this investigation - i.e. whether or not the brush configuration and commutator speed are factors in the oxidation and reduction processes involved in the formation of surface films and therefore factors in determining the altitude where brush dusting commences.

It is suggested that unless it is desired to attempt to make such a determination on a particular machine, such testing can best be done with a small chamber only large enough to enclose the commutator and brush holders. The commutator can be driven from outside the chamber through a sealed shaft. The problem of drive motor brush wear is thus eliminated. In addition, humidity control and the flushing out of contaminating vapors are much more easily achieved because of the smaller volumes of air that have to be handled. The problem of air leakage is also greatly reduced because of the fewer joints.

It is also suggested that preliminary tests with unloaded brushes are unnecessary, and therefore the tests should commence with electrically loaded brushes. This will insure the formation of a good representative surface film during the running-in period. It will also permit some temperature control of the brushes by varying the load current if this becomes necessary.

# APPENDIX

## APPENDIX A

Estimate of the Adsorption Capacity of Aluminum Oxide Compared with the Moisture Content of the Vacuum Chamber

I Adsorption Capacity of two pounds of Aluminum Oxide

A. Assumptions:

1. adsorption of a single monolayer of water molecules.

2. surface area of aluminum oxide powder = 50 meter$^2$/gram.

B. Quantities involved:

1. surface area of 2 lbs (907.2 grams) of $Al_2O_3$ = 45,360 $m^2$ = A

2. cross section of a water molecule = 10.5 $\mathring{A}^2$ = B

3. Avogadro's Number = 6.02 $10^{23}$ = $N_A$

C. Number of moles of water in one monolayer = $n_1 = \frac{A}{B\,N_A}$

$$n_1 = \frac{(45,360) \times 10^4 \text{ cm}^2}{(10.5 \times 10^{-16})\text{cm}^2 \times (6.02 \times 10^{23})}$$

$n_1$ = 0.716 moles

II Moisture content of the Vacuum Chamber

A. Assumptions:

1. Temperature = 25° C; Relative Humidity = 72%

B. Quantities involved:

1. water vapor pressure = 17 mm. Hg. = 0.0224 atmospheres.

2. R = universal Gas Constant = $8205 \frac{\text{cm}^3 \times \text{Atmos}}{°\text{K} \times \text{Mole}}$

3. $T = 273^{\circ} + 25^{\circ} = 298^{\circ}$ K

4. $V$ = volume of vacuum chamber = 198,200 $cm^3$

C. $P_{H_2O}V = n_2RT$

$$n_2 = \frac{(2.24 \times 10^{-2}) \times (198.2 \times 10^3}{(8.205 \times 10^3) \times 298} = 0.0018 \text{ moles}$$

III $n_1 \gg n_2$

# APPENDIX B

## Brush and Motor Description

A. **Test Brushes T-1, T-2, T-3, and T-4**

1. **3/4" x 1/4" x 1/4"   cartridge type**

2. **Spring pressure : 8 psi**

3. **Manufacturer : Stackpole Carbon Company;**
   **St. Marys, Pennsylvania**

4. **Manufacturer's designation : "Grade 51"**

B. **Drive Motor Brushes**

1. **Size: 23/32" x 1/2" x 1/4"**

2. **Application : For motor identified below**

3. **Manufacturer : Stackpole Carbon Company**

4. **Manufacturer's designation : "Grade 57"**

C. Motor

1. Trade name : "DUMORE" ( a bench grinder motor)

2. Catalogue No. 5-021

3. Input: 115 volts, 5.6 amperes, d-c or 0-60 cycles a-c

4. RPM : full load 10,000
   no load 15,500

## APPENDIX C

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